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Study on the supply capacity of crop residue as energy in rural areas of Heilongjiang province of China

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ABSTRACT

Heilongjiang is the most northeastern province of China. The climate of Heilongjiang consists of very cold winters, leading to large energy demands for space heating by local residents. Rich food crop yields in Heilongjiang results in large amounts of crop residues. To fully accommodate rural energy demand and facilitate the effective utilization of crop residues, this study builds a mathematical model of supply capacity of crop residues as energy, then, based on the data from a field survey and literature review, calculates the local annual effective heat demands for living, the supply rates for effective heat of different crop residue utilization patterns, and the supply capacities of crop residues as energy in rural areas of Heilongjiang. Results show that the supply capacity of traditional direct burning of crop residues is less than 1, indicating that direct burning of crop residues cannot fully supply rural living heat demands. The supply capacity of densification is more than 1.6, indicating that introducing densification can not only achieve full supply for rural living heat demands, but also result in a large proportion of crop residues remaining for other uses. Because part of the crop residues is converted to products other than gas, dry distillation can only supply 55% of the rural living heat demands. Introducing efficient technologies of crop residue utilization for energy in rural areas of Heilongjiang can make the available amount of energy from crop residues larger than the amount of energy demand. This study found that the combination of densification and dry distillation of crop residues can be used as a high-efficiency centralized supplement of living heat, achieving multiple benefits such as use of alternatives to fossil fuel energy, economic development, environment protection, and improvement in quality of life.

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Nomenclature

q_c/q_h	effective heat index for cooking/heating, MJ/(capita a) and MJ/(m^2 a)
m_c/m_h	annual consumption of a type of cooking/heating fuel, (kg/a)
v_c/v_h	calorific value of a type of cooking/heating fuel, (MJ/kg)
η_c/η_h	thermal efficiency of cooking/heating
n	household population, (capita)
A	residential area, (m^2)
Q_c/Q_h	annual demanded effective heat of cooking/heating, (MJ/a)
N	rural population, (capita)
a	rural residential area per capita, (m^2/capita)
r_c/r_h	supply rate for effective heat of cooking/heating, (MJ/kg)
e	material utilizing coefficient, (kg/kg or m^3/kg)
v	calorific value of fuel processed by crop residues, (MJ/kg or MJ/m^3)
e'	net material utilizing coefficient of dry distillation, (m^3/kg)
$p_c/p_v/p_t$	material utilizing coefficients of charcoal, tar, and pyroligneous acid, (kg/kg)
C	supply capacity of crop residues as energy
M_{avl}	annual available amount of crop residues, (kg/a)
$M_{dmd.c}/M_{dmd.h}$	annual demand amount of crop residues for cooking/heating, (kg/a)
Y	annual grain yield, (kg/a)
s	residue production ratio
F	sown area of a crop, (hm^2)
δ	suitable annual recycling amount of a crop, (kg/(hm^2 a))

1. Introduction

Heilongjiang is the northernmost and easternmost province in China, with an area of 473,000 km^2 and a population of more than 38 million, of which nearly a half is rural. The climate of Heilongjiang is classified as a temperate continental monsoon climate; therefore, Heilongjiang is very cold in the winter, leading to large energy demands for space heating by local residents. In Heilongjiang, more than 90% of the cultivated fields are sown with rice, corn, soybean, and wheat. The provincial crop yield per capita is the highest in China [1]; thus, the per capita amount of crop residues in rural areas of Heilongjiang is also large. Due to the coexistence of large heating fuel demands and large crop residue yields in Heilongjiang, it is necessary to judge whether the crop residues could be used to fully supply the heating demands of local rural residents.

Cooking and heating in cold regions are essential energy-using activities for basic living needs. Because both the activities use heat from burning fuels, this energy can be called “living heat.” In rural areas of Heilongjiang, living heat accounts for the main proportion of energy consumption of residents [2]. Recently, most of the rural households have been directly burning crop residues for cooking and heating. Given the cold winters in Heilongjiang and the low efficiency of direct burning of crop residues, the amount of crop residues used as heating fuel in rural households is large, leading to shortages of crop residues in some rural regions. Given the shortcomings in direct burning of crop residues of short combustion duration, low flame temperature, indoor environmental pollution, and the costs attributed to the time and effort needed for fuel collecting and feeding, some richer rural residents would rather pay for fossil fuels, such as coal and liquefied petroleum gas (LPG), and abandon the use of free renewable crop residues, thus leading to the inefficient use and surplus of crop residues in the region.

To improve the performance of crop residues as domestic fuel and to make full and efficient use of crop residues in rural areas, researchers in China have been studying many kinds of technologies to utilize crop residues as energy [3]. Considering objective conditions such as the local climate and crop species, it has been found that suitable technologies of crop residue utilization as energy in Heilongjiang are densification and dry distillation. The densification of crop residues refers to pressing crop residues into pellets with a higher density, improving the energy density and combustion efficiency, thus making them easy to transport, store, and use. The dry distillation of crop residues refers to heating crop residues in the absence of oxygen, which produces charcoal, tar, pyroligneous acid, and gas. The quality of the gas produced through distillation meets the requirement for urban gas in China. The other three products of distillation (charcoal, tar, and pyroligneous acid) can be sold as commodities to achieve economic benefits.

To achieve full and efficient use of crop residues in a region, the first and foremost task is to assess whether the available amount of local crop residues can meet the region's actual needs. Previous research has examined the available amount of crop residues for various regions. Scarlat et al. provided an assessment of the amount of available crop residues for bioenergy production in the European Union (EU) [4]. Scarlat et al. [4] found large spatial and temporal variations of available crop residues within EU nations and determined that the variation in available crop resides might eventually result in shortages of the biomass supply. Cui et al. and Bi et al. estimated the crop residue resources of China using two different methods [5,6]. The results included the total amount and main types of crop residues in China, and the spatial distribution of crop residues that can be utilized as energy. Other previous research has studied in more depth the feasibility of crop residue utilization technologies based on the estimation of the regional available amount of crop residues. Some of these studies involved collecting statistical information or conducting investigations to assess and predict the available amount and utilization status of crop residues in some regions, which provided developmental targets and effective ways for crop residue utilization [7–,8,9]. Others studies estimated the types, yields, distributions, and other availability characteristics of crop residues in a nation or region through the use of GIS and remote sensing technology, and then discussed the local feasibility of some particular crop residue utilization technologies such as crop residue power plants, bioethanol, and densification [10–15].

The existing studies discussed above have resulted in great improvements in crop residue utilization. However, these existing studies have generally focused on the available amount of crop residues but gave simple estimations, instead of in-depth studies, on the actual demand of crop residues. Without an official index of rural living heat, it is hard to estimate the demand; therefore, in China, there are no detailed studies on crop residue supply capacity based on the local demand of living heat.

This study defines “effective heat” as the actual amount of heat received by heat consumers, “supply rate for effective heat” as the amount of effective heat for living that is supplied by per unit crop residues as energy with a crop residue utilization technology, and

"supply capacity of crop residues as energy" as the ratio between the amount of crop residues that can be used as energy in a region (hereinafter referred to as the "available amount") and the amount of crop residues that are demanded for completely supplying local effective heat for living (hereinafter referred to as the "demanded amount"). Given the definitions above, this study calculates the indices of effective heat for cooking and heating based on a field survey in rural areas of Heilongjiang, and further calculates the annual amount of demanded effective heat by the indices. Meanwhile, the supply rates for effective heat of densification, dry distillation, and direct burning of crop residues are calculated with corresponding literature data. Finally, according to the basic conditions of rural areas of Heilongjiang in recent years, the supply capacities of densification, dry distillation, and direct burning of crop residues are calculated and analyzed.

2. Methodology

The methodology of this study combines theoretical analysis and data investigation. The results of effective heat demands for living, the supply rate for effective heat, and the supply capacity of crop residues as energy are all calculated by theoretical formulae, while the essential data involved in the formulae are collected through investigations.

2.1. Calculation method of effective heat

In this study, the annual per capita effective heat for cooking is described as the effective heat index for cooking, while the annual per area effective heat for heating is described as the effective heat index for heating.

The effective heat index for cooking can be expressed as the ratio between the total amount of effective heat for cooking that is supplied by all types of cooking fuel in a year and specific total population, and is calculated using the following equation:

$$q_c = \frac{\sum m_c v_c \eta_c}{n} \tag{1}$$

where q_c is the effective heat index for cooking [MJ/(capita a)], m_c is the annual consumption of a type of cooking fuel [kg/a], v_c is the calorific value of the fuel [MJ/kg], η_c is the thermal efficiency of the cooking appliance corresponding to this type of fuel, and n is the population [capita].

Similarly, the effective heat index for heating can be expressed as the ratio between the total amount of effective heat for heating that is supplied by all types of heating fuel in a year and total residential area, and is calculated using the following equation:

$$q_h = \frac{\sum m_h v_h \eta_h}{A} \tag{2}$$

where q_h is effective heat index for heating [MJ/(m^2 a)], m_h is the annual consumption of a type of heating fuel [kg/a], v_h is the calorific value of the fuel [MJ/kg], η_h is the thermal efficiency of the heating appliance corresponding to this type of fuel, and A is residential area [m^2].

In this study, the calculation of effective heat indices for cooking and heating are based on the data collected through field survey. For both q_c and q_h after data verification, the mean of all calculation results from survey households is taken as the final result of effective heat index. The methods of data verification and mean calculation for q_c or q_h are elaborated in Section 2.4.1, mainly as Eqs. (20) and (15).

According to the effective heat index for cooking/heating, the annual demanded effective heat of cooking and heating in a rural area is calculated using the following equations:

$$Q_c = \overline{q}_c N \tag{3}$$

$$Q_h = \overline{q}_h N a \tag{4}$$

where Q_c/Q_h is the annual demanded effective heat for cooking/heating [MJ/a], $\overline{q}_c/\overline{q}_h$ is the mean of all q_c/q_h from survey households after data verification, N is the local rural population [capita], and a is the local rural residential area per capita [m^2/capita].

2.2. Calculation method of supply rates for effective heat

In order to compare the material utilization rate of different technologies of crop residue utilization as energy, the supply rate for effective heat can be calculated by the following equations:

$$r_c = v \eta_c e \tag{5}$$

$$r_h = v \eta_h e \tag{6}$$

where r_c/r_h is the supply rate for the effective heat for cooking/heating of the technology [MJ/kg], e is the amount of fuel produced per unit crop residues with the technology (called the "material utilizing coefficient") [kg/kg or m^3/kg], v refers to the calorific value of fuel produced with the technology [MJ/kg or MJ/m^3], and η_c/η_h refers to the thermal efficiency of the cooking/heating appliance corresponding to the fuel.

The products of dry distillation are not only gas, but also charcoal, tar, and pyroligneous acid, which can be sold as commodities. Therefore, only part of the crop residues is distilled into gas. In order to check the effectiveness of integrated utilization of crop residues with dry distillation, the definition of the "net material utilizing coefficient" is given as the ratio between the amount of produced gas and the amount of crop residues excluding the amount producing charcoal, tar, and pyroligneous acid. The net material utilizing coefficient can be calculated by the following equation:

$$e' = \frac{e}{1 - p_c - p_v - p_t} \tag{7}$$

where e' is the net material utilizing coefficient of dry distillation [m^3/kg] and p_c, p_v, and p_t are the material utilizing coefficients of charcoal, tar, and pyroligneous acid, respectively [kg/kg].

The supply rate for effective heat calculated according to net material utilizing coefficient of dry distillation can be called the "net supply rate for effective heat".

2.3. The mathematical model of supply capacity of crop residue as energy

When a type of crop residue utilization technology is applied in a region, the supply capacity of crop residues as energy can be calculated using the following equation:

$$C = \frac{\sum M_{avl}}{M_{dmd.c} + M_{dmd.h}} \tag{8}$$

where C is the supply capacity of crop residues as energy, $\sum M_{avl}$ is the total annual available amount of all kinds of crop residues [kg/a], and $M_{dmd.c}/M_{dmd.h}$ is the annual demanded amount of crop residues for cooking/heating [kg/a].

The annual available amount of crop residues (M_{avl}) is the annual crop residue yield after removing the amount used for livestock feed, fertilizer (also called residue recycling), mushroom production, and industrial material, as well as the amount of crop residues lost in harvesting and storage. The loss of crop residues mostly occurs in cultivated fields and can be considered included in the amount of residue recycling. Traditionally in China, rural residents use livestock wastes as biofertilizer. Recently in Heilongjiang,

the annual amount of crop residues for livestock feed is less than that for recycling, and the proportion of crop residues for mushroom production and industrial material is so small that can be ignored [8]. Therefore, M_{avl} can be calculated using the following equation:

$$M_{avl} = Ys - F\delta \tag{9}$$

where Y is the annual grain yield in the region [kg/a], s is the ratio between residue yield and grain yield (called the "residue production ratio"), F is the sown area of the crop in the region [hm^2], and δ is the suitable annual recycling amount of the crop [kg/(hm^2 a)].

The annual demanded amount of crop residues for cooking/heating ($M_{dmd.c}/M_{dmd.h}$) can be calculated using the following equations:

$$M_{dmd.c} = \frac{Q_c}{r_c} \tag{10}$$

$$M_{dmd.h} = \frac{Q_h}{r_h} \tag{11}$$

By substituting Eqs. (9)–(11) and (3)–(6) into Eq. (8), the mathematical model of supply capacity of crop residues as energy can finally be derived as:

$$C = \frac{\sum(Ys - F\delta)}{Q_c/r_c + Q_h/r_h} = \frac{ve\eta_c\eta_h \sum(Ys - F\delta)}{N(\eta_h\overline{q}_c + \eta_c\overline{q}_h a)} \tag{12}$$

Fig. 1 illustrates the flow in and flow out for each equation from Sections 2.1–2.3. The v and η_c/η_h that flow into Eqs. (5) and (6) are placed in a hexagon to show that they are related to processed fuel by crop residues, which differ from the v_c/v_h and η_c/η_h that flow into Eqs. (1) and (2).

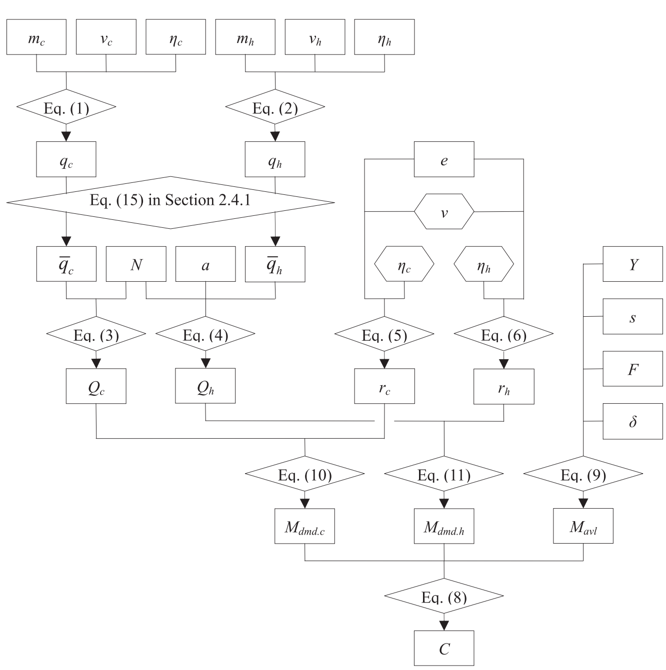

Fig. 1. Flow in and flow out for various equations.

2.4. Data collection

The essential data involved in the theoretical analysis in Sections 3.1–3.3 were collected through investigations. As official indices of rural living heat in China do not currently exist, this study conducted a field survey in rural areas of Heilongjiang to provide basic data for calculating effective heat indices for living in Section 3.1. The basic conditions of rural areas of Heilongjiang and data of crop residues, utilization technologies, and current energy use patterns were obtained from literature review.

2.4.1. Field survey program and data verification

The field survey considers the rural households in Heilongjiang as the survey objects. The key-point survey and sampling survey were conducted successively.

Most of the rural population and cultivated lands in Heilongjiang are located in the middle and northeastern plains, therefore, these two plains were selected as the key-point survey areas, in which a two-stage sampling survey was subsequently conducted. In the first stage, 19 villages in the key-point survey areas, which are from 15 county level divisions and 8 prefectural level divisions (Fig. 2), were randomly sampled. In the second stage, 8 households in each selected village were randomly sampled. A uniformed questionnaire was presented to each selected household. A total of 152 copies of the questionnaire were sent out, of which 133 copies were returned; 120 of these 133 copies were used in the study. The distribution of the 120 available questionnaires is presented in Table 1. The prefectures in Table 1 are listed in descending order according to the number of rural households [16].

All necessary information for Eqs. (1) and (2) was included in the questionnaires. The returned data of each available questionnaire are listed in Table A1.

The annual effective heat indices for cooking and heating, which are calculated using Eqs. (1) and (2) according to the data from the questionnaires, had to be verified. For two-stage sampling with $(1-\alpha)$ confidence, the confidence interval and relative limit of error are:

$$(x_{inf}, x_{sup}) = \overline{x} \pm t_{\alpha/2}\sqrt{s_{\overline{x}}^2} \tag{13}$$

$$\delta_x = \frac{t_{\alpha/2}\sqrt{s_{\overline{x}}^2}}{\overline{x}} \tag{14}$$

where x_{inf} and x_{sup} are the lower and upper limits of the confidence interval, δ_x is the relative limit of error, $t_{\alpha/2}$ is the $\alpha/2$ quantile of standard normal distribution, with the common α as 0.3173/0.0500/0.0100 and corresponding $t_{\alpha/2}$ as 1.00/1.96/2.58, and $\overline{x}$ and $s_{\overline{x}}^2$ are the mean and variance, respectively, calculated using the following equations [17]

$$\overline{x} = \frac{\sum_{i=1}^{k} N_i\overline{x}_i}{\sum_{i=1}^{k} N_i} \tag{15}$$

$$s_{\overline{x}}^2 = \frac{f(1-g)}{n_0}s_{intra}^2 + \frac{1-f}{k}s_{inter}^2 \tag{16}$$

where k is the unit number of the first stage of sampling, N_i is the sampling population in unit i, $\overline{x}_i$ is the mean of unit i, f/g is the sampling ratio of the first/second stage, n_0 is the number of total sampling population, and s_{intra}^2 and s_{inter}^2 are intraclass variance and interclass variance, respectively, calculated using the following equations:

$$s_{intra}^2 = \frac{1}{k}\sum_{i=1}^{k} s_i^2 \tag{17}$$

$$s_{inter}^2 = \frac{1}{k-1}\sum_{i=1}^{k} (\overline{x}_i - \overline{x})^2 \tag{18}$$

where s_i^2 is the variance of unit i.

At the end of 2012, there were 8.34×10^3 villages and 5.14×10^6 rural households in Heilongjiang, indicating an average of about 616 households per village [16]. With this information, the sampling ratio of the first/second stage can be calculated, resulting in $f = 19/(8.34 \times 10^3) = 2.28 \times 10^{-3}$ and $g = 120/19/616 = 0.01$. Due

Fig. 2. Locations of the survey villages in Heilongjiang.

Table 1
Overview on the distribution of the survey areas and available questionnaires.

Prefecture	Rural households	Surveyed villages	Available households in each village
Harbin	1,344,102	5	7, 5, 7, 7, 4
Suihua	1,006,938	4	8, 3, 8, 5
Qiqihar	960,649	2	5, 8
Daqing	366,313	2	5, 5
Jiamusi	360,690	1	7
Mudanjiang	313,413	2	5, 8
Heihe	223,589	2	8, 8
Jixi	194,171	1	7

to the difficulty in obtaining the household number for each village, this study assumes $N_i = const = 616$ $(i = 1,2,\ldots,k)$.

Substituting Eqs. (15)–(18) and $N_i = const$ into Eq. (13), the confidence interval and relative limit of error with $(1-\alpha)$ confidence can be calculated using the following equations:

$$(x_{inf}, x_{sup}) = \frac{1}{k}\sum_{i=1}^{k}\bar{x}_i \pm t_{\alpha/2}\sqrt{\frac{f(1-g)}{n_0 k}\sum_{i=1}^{k}s_i^2 + \frac{(1-f)}{k(k-1)}\sum_{i=1}^{k}\left(\bar{x}_i - \frac{1}{k}\sum_{i=1}^{k}\bar{x}_i\right)^2} \quad (19)$$

$$\delta_x = \frac{t_{\alpha/2}}{\sum_{i=1}^{k}\bar{x}_i}\sqrt{\frac{kf(1-g)}{n_0}\sum_{i=1}^{k}s_i^2 + \frac{(1-f)}{(k-1)}\sum_{i=1}^{k}\left(\bar{x}_i - \frac{1}{k}\sum_{i=1}^{k}\bar{x}_i\right)^2} \quad (20)$$

Overall, the whole procedure of the field survey program and data verification can be viewed in Fig. 3.

2.4.2. The collection of literature data

Table 2 presents the basic conditions of rural areas of Heilongjiang [1]. The sown areas and yields include the four main crops of Heilongjiang, rice, corn, soybean, and wheat.

The residue production ratios and suitable annual recycling amounts of the four main crops in Heilongjiang are presented in Table 3 [18]. To maximize the available amounts, the suitable annual recycling amounts in Table 3 are minimized.

The main technical parameters of densification, dry distillation, and direct burning of crop residues are listed in Table 4.

According to the field survey, most of the rural households in Heilongjiang use crop residues for cooking and heating by direct burning. The LPG in cylinders and coal are the main fossil energy for cooking and heating, respectively. The calorific values and thermal efficiencies involved in the field survey are presented in Table 5.

3. Results and discussion

Based on the collected data from the field survey and literature review in Section 2.4, the indices and annual demands of effective heat for living, the supply rates for effective heat, and the supply capacities of crop residues as energy can be calculated according to the calculation methods in Sections 2.1, 2.2, and 2.3, respectively.

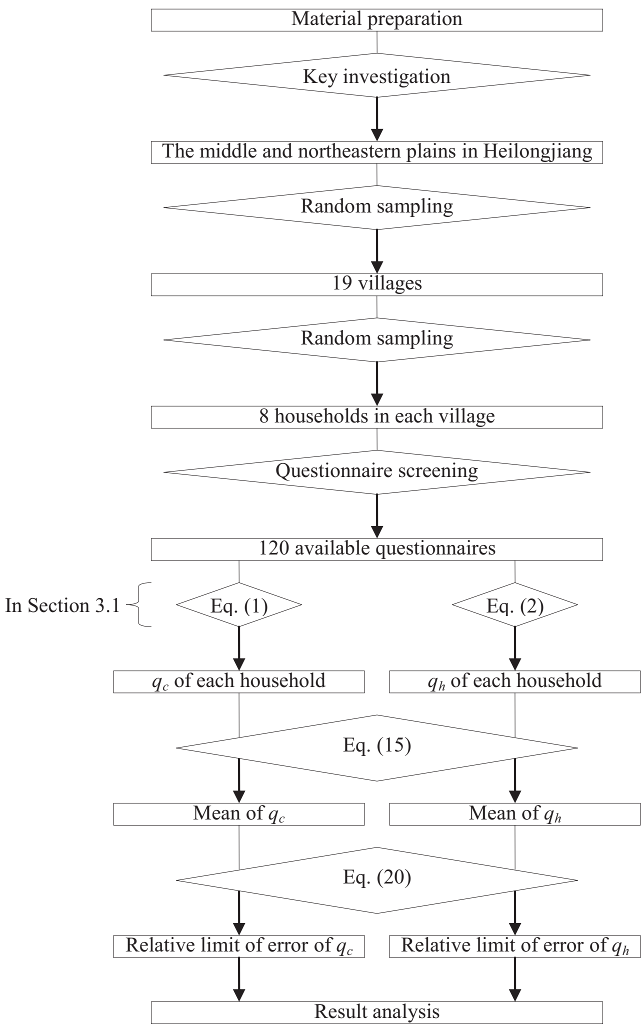

Fig. 3. Procedure of the field survey program and data verification.

3.1. The indices and annual demands of effective heat for living

According to Table 5 and Table A1, the annual per capita effective heat for cooking and the annual per area effective heat for heating of each household are calculated by Eqs. (1) and (2). Furthermore, for the two indices, the means and relative limits of error are calculated by Eqs. (15) and (20). The results are presented in Table 6.

It can be seen in Table 6 that for both the effective heat indices for cooking and heating, the relative limits of error are more than 10% with each $(1-\alpha)$. The reasons for this phenomenon can be explained as follows: (1) some rural households sometimes use electricity for cooking; thus, the consumption amount is difficult to quantify and not included in the calculation, which causes some results of effective heat for cooking to be smaller than actual consumption; (2) in winter, some rural households heat only the main living rooms of their houses so that their heating areas are much smaller than their total residential areas, thus making the effective heat index for heating smaller when dividing the annual effective heat for heating by residential area; (3) some rural residences have poor insulation of the building envelope or poor air tightness of doors and windows, enlarging their heating load and resulting in higher effective heat for heating consumption; (4) In winter, when the outdoor temperature is not very low, in order to save heating fuel (mainly coal), many rural households only use the heat released to their rooms while cooking, which is classified as cooking by some households and as heating by others, causing deviations in the results.

From Table 6, for both the effective heat indices for cooking and heating, the relative limits of error are about 20% with $(1-\alpha)=95.00\%$. Considering the diversity and uncertainty of heat use for living in rural households of Heilongjiang, these relative limits of error are reasonable. Therefore, the mean value estimation of annual effective heat indices in Table 6 can be accepted.

According to the results of calculation and verification for effective heat indices and the average values of rural population and per capita residential area shown in Table 2, the annual demands of effective heat for living in rural areas of Heilongjiang can be calculated using Eqs. (3) and (4). The results of this calculation are presented in Table 7.

It can be seen from Table 7 that the annual demand of effective heat for heating is nearly 10 times that for cooking in rural areas of Heilongjiang. Therefore, reducing the energy consumption of heating is the key to rural building energy efficiency. Enhancing the insulation of the building envelope and the air tightness of doors and windows in rural residences can reduce the heating loads of the building in the winter, leading to the reduction of energy consumption in rural households.

Table 2
Basic conditions of rural areas of Heilongjiang.

	2010	2011	2012	Average
Rural population [10^6 capita]	17.06	16.68	16.52	16.75
Rural residential area per capita [m^2/capita]	22.8	24.8	24.8	24.1
Sown area [10^6 hm^2]				
Rice	2.7688	2.9456	3.0698	2.9281
Corn	4.3684	4.5874	5.1906	4.7155
Soybean	3.5479	3.2017	2.6638	3.1378
Wheat	0.2800	0.2978	0.2101	0.2626
Yield [10^9 kg/a]				
Rice	18.439	20.621	21.712	20.257
Corn	23.244	26.758	28.879	26.294
Soybean	5.850	5.413	4.634	5.299
Wheat	0.925	1.038	0.700	0.888

Table 3
Residue production ratios and suitable annual recycling amounts.

	Rice		Corn		Soybean	Wheat
	Straw	Bran	Cob	Stalk	Straw	Straw
Residue production ratio	1.0	0.21	0.21	1.15	1.6	1.3
Suitable annual recycling amount [kg/(hm^2 a)]	3000	0	0	4500	3000	3000

Table 4
Technical parameters of densification, dry distillation, and direct burning of crop residues.

	Densification	Dry distillation				Direct burning
		Charcoal	Tar	Pyroligneous acid	Gas	
Material utilizing coefficient	0.9 [kg/kg] [19]	0.3 [kg/kg] [20]	0.05 [kg/kg] [20]	0.25 [kg/kg] [20]	0.3 [m^3/kg] [20]	1
Calorific value	14.654 [MJ/kg] [21]	–	–	–	12.54 [MJ/m^3] [22]	14.654 [MJ/kg]
Cooking thermal efficiency	0.40 [21]	–	–	–	0.55 [23]	0.10
Heating thermal efficiency	0.75 [21]	–	–	–	0.85 [24]	0.45

Table 5
Calorific values and thermal efficiencies.

Energy type	Calorific values [MJ/kg] [25]	Appliance type	Thermal efficiency
Firewood	16.726	Biomass stove for cooking	10% [26]
Crop residues	14.654	Kang (with biomass stove) for heating	45% [26]
LPG	50.179	LPG stove for cooking	55% [27]
Coal	20.908	Kang – indigenous heating system (with coal stove) for heating	70% [28,29]

Table 6
Means and relative limits of error of annual effective heat indices.

Index type	Mean	Relative limit of error		
		$(1-\alpha)=68.27\%$	$(1-\alpha)=95.00\%$	$(1-\alpha)=99.00\%$
Cooking	935 [MJ/(capita a)]	11.4%	22.4%	29.5%
Heating	364 [MJ/(m^2 a)]	12.9%	25.2%	33.2%

Table 7
Annual demands of effective heat for living in rural areas of Heilongjiang.

	Annual effective heat index	Annual demand of effective heat [10^9 MJ/a]
Cooking	935 [MJ/(capita a)]	15.67
Heating	364 [MJ/(m^2 a)]	147.29
Total	–	162.96

Table 8
Supply rates for effective heat of densification, dry distillation, and direct burning.

	Supply rate for effective heat [MJ/kg]		Net material utilizing coefficient [m^3/kg]	Net supply rate for effective heat [MJ/kg]	
	Cooking	Heating		Cooking	Heating
Densification	5.28	9.89	–	–	–
Dry distillation	2.07	3.20	0.75	5.17	7.99
Direct burning	1.47	6.59	–	–	–

3.2. The supply rates for effective heat

According to Table 4, the supply rates for effective heat of densification, dry distillation, and direct burning of crop residues can be calculated using Eqs. (5) and (6). The results of this calculation are presented in Table 8. The net material utilizing coefficient, calculated using Eq. (7), and the net supply rate for effective heat, calculated by substituting e for e' in Eq. (6), of dry distillation are also presented in Table 8.

Table 8 shows that: (1) the supply rates of densification both for cooking and heating are the highest supply rates of all technologies, indicating that densification can make the most adequate use of the heat contained in crop residues; (2) for cooking, the supply rate of dry distillation is higher than that of direct burning, but for heating, the supply rate of dry distillation is less than 1/2 of that of direct burning, indicating that for utilizing heat from crop residues, dry distillation is more suitable for supplying cooking demand; (3) for cooking, the net supply rate of dry distillation is much higher than that of direct burning and slightly lower than that of densification. For heating, the net supply rate of dry distillation is also significantly higher than that of direct burning, indicating that dry distillation has a good effectiveness for integrated utilization of crop residues.

3.3. The supply capacities of crop residues as energy

According to the data in Section 2.4.2 and calculation results in Sections 3.1 and 3.2, the supply capacities of crop residues as energy in Heilongjiang can be calculated using Eq. (12). For densification, dry distillation, and direct burning, the results are 1.66, 0.55, and 0.90, respectively.

From the calculation results, some analysis can be made as follows:

(1) The supply capacity of densification is more than 1.6, the highest supply capacity of all technologies, indicating that introducing densification into Heilongjiang cannot only achieve full supply for rural living heat demands, but also result in a large proportion of crop residues remaining for other uses. Therefore, in some rural regions with problems of crop residue shortage, introducing densification would likely be the best solution.

(2) The supply capacity of dry distillation is 0.55, the lowest supply capacity of all technologies, indicating that only 55% of the rural living heat demands can be supplied by this technology in Heilongjiang. Therefore, dry distillation is only suitable for rural regions with sufficient crop residues. Moreover, according to Section 3.2, the supply rate of dry distillation for cooking is higher than that of direct burning, and dry distillation has a good effectiveness for integrated utilization when considering all products of dry distillation. Therefore, it is reasonable to combine densification with dry distillation in some rural regions with relative abundant crop residues, with dry distillation preferably used for cooking, thus compensating for the low supply capacity of dry distillation by densification and leading to triple benefits to local rural residents through achieving full supply for rural living heat demands, improving the fuel quality, and obtaining additional economic benefits from other distilling products.

(3) The supply capacity of traditional direct burning is less than 1, indicating that it cannot accommodate full supply for rural living heat demands in Heilongjiang. In addition, as mentioned in Section 1, there are many shortcomings of direct burning. Therefore, in rural areas of Heilongjiang, replacing traditional direct burning with other utilization technologies of crop residues is necessary.

4. Conclusions

In rural areas of Heilongjiang Province in China, the annual per capita effective heat for cooking is 935 MJ/(capita a), while the annual per area effective heat for heating is 364 MJ/(m^2 a). The annual demands of effective heat for cooking and heating are 15.67×10^9 and 147.29×10^9 MJ/a, respectively, which show that heating accounts for most of the effective heat for living. Therefore, reducing the energy consumption of heating is the key to rural building energy efficiency.

Densification can make the most adequate use of the heat contained in crop residues. Dry distillation has a good effectiveness for integrated utilization of crop residues, but for utilizing heat from crop residues, dry distillation is more suitable for cooking.

In Heilongjiang, the supply capacity of traditional direct burning is less than 1, indicating that it cannot fully supply rural living heat demands. The supply capacity of densification is more than 1.6, indicating that introducing densification can not only achieve full supply for rural living heat demands, but also result in a large proportion of crop residues remaining for other uses. Because part of the material is converted to other products, dry distillation can only supply 55% of the rural living heat demands. However, it is reasonable to combine densification with dry distillation, with dry distillation preferably used for cooking, thus leading to triple benefits to local rural residents through achieving full supply for rural living heat demands, improving the fuel quality, and obtaining additional economic benefits from other distilling products.

Introducing technologies of crop residue utilization as energy in rural areas of Heilongjiang can make the available amount of crop residues larger than the demanded energy amount. Moreover, from a macro view, the combination of densification and dry distillation can substitute high-efficiency centralized supplement of living heat for traditional domestic energy use patterns, achieving multiple benefits such as use of alternatives to fossil fuel energy, economic development, environment protection, and improvement in the quality of life. Therefore, developing the feasible technology of centralized heat or gas supply with crop residues as energy sources in rural areas is worthy of further study, which the authors of this study plan to conduct.

Appendix A

See Table A1.

Table A1
Returned data of each available questionnaire.

HN[a]	VN[b]	Prefecture	HP[c]	HRA[d]	ACEC[e] [kg]			AHEC[f] [kg]		
					Firewood	CR[g]	LPG[h]	Firewood	CR	Coal
1	1	Harbin	4	80	500	0	100	4500	0	1000
2	1	Harbin	5	70	225	50	50	25	200	1000
3	1	Harbin	3	65	400	0	50	3600	0	0
4	1	Harbin	5	70	585	195	50	65	455	1000
5	1	Harbin	5	60	600	700	50	1400	300	0
6	1	Harbin	4	90	500	50	75	4500	50	1000
7	1	Harbin	4	70	450	250	50	50	250	1000
8	2	Harbin	2	80	500	125	15	0	125	1000
9	2	Harbin	4	60	675	675	30	75	75	1000
10	2	Harbin	2	80	100	500	15	900	500	0
11	2	Harbin	2	50	0	750	15	0	500	0
12	2	Harbin	4	85	500	225	60	0	25	1000
13	3	Harbin	5	70	250	3750	75	250	3750	1500
14	3	Harbin	4	75	40	4200	50	60	2800	0
15	3	Harbin	2	90	200	4500	50	300	3000	1000
16	3	Harbin	7	90	50	7500	50	450	0	1500
17	3	Harbin	4	80	200	3000	50	300	2000	1000
18	3	Harbin	4	80	0	4200	0	250	2800	0
19	3	Harbin	4	90	300	1500	25	1200	6000	1000
20	4	Harbin	5	75	0	2400	0	100	600	2000
21	4	Harbin	6	110	0	750	0	0	750	2000
22	4	Harbin	5	70	0	750	0	0	750	1500
23	4	Harbin	3	70	0	400	0	0	100	1500
24	4	Harbin	5	100	0	1500	0	0	1500	2000
25	4	Harbin	10	160	0	1200	0	0	1800	4000
26	4	Harbin	2	40	0	500	0	0	500	500
27	5	Harbin	3	70	0	1000	0	0	250	1000
28	5	Harbin	6	90	0	1000	0	0	250	1500
29	5	Harbin	5	120	0	3200	0	0	800	1000
30	5	Harbin	5	135	0	2000	0	0	500	1500
31	6	Suihua	2	100	0	3150	0	0	1350	0
32	6	Suihua	4	90	0	2250	0	0	2250	1000
33	6	Suihua	4	100	0	2400	0	0	1600	1000
34	6	Suihua	4	100	0	2800	0	0	1200	1500
35	6	Suihua	3	100	0	1750	0	0	1750	500
36	6	Suihua	5	70	250	2250	0	0	2250	1000
37	6	Suihua	3	160	0	3600	0	0	400	3000
38	6	Suihua	3	160	0	400	0	0	3600	3000
39	7	Suihua	5	50	0	10000	0	0	0	1500
40	7	Suihua	2	60	0	150	50	0	1350	500
41	7	Suihua	5	100	1350	450	36	150	1050	1000
42	8	Suihua	3	98	0	2500	0	100	2500	0
43	8	Suihua	5	120	75	3750	60	75	3750	2000
44	8	Suihua	3	95	0	1800	0	100	2700	0
45	8	Suihua	6	95	0	1400	30	500	2100	1000
46	8	Suihua	5	80	12.5	2000	40	12.5	2000	1000
47	8	Suihua	3	40	60	2250	0	90	1500	0
48	8	Suihua	3	30	80	2550	0	120	1700	0
49	8	Suihua	4	85	0	2000	20	0	2000	1000
50	9	Suihua	5	80	0	2250	0	500	750	1000
51	9	Suihua	4	110	100	2400	100	900	600	1500
52	9	Suihua	3	45	0	700	40	1000	300	3000
53	9	Suihua	4	80	450	50	150	4050	450	0

54	9	Suihua	3	70	750	45	20	6750	5	0
55	10	Qiqihar	3	60	0	1600	0	0	2400	0
56	10	Qiqihar	3	60	0	1400	80	0	600	1000
57	10	Qiqihar	4	60	0	375	50	0	1125	1000
58	10	Qiqihar	6	80	0	2700	0	0	6300	0
59	10	Qiqihar	3	60	0	2450	80	0	1050	1000
60	11	Qiqihar	4	110	0	7665	14	0	3285	0
61	11	Qiqihar	4	95	0	2000	0	0	2000	0
62	11	Qiqihar	5	120	0	2000	28	0	2000	2500
63	11	Qiqihar	5	100	750	750	50	750	750	1000
64	11	Qiqihar	3	110	0	4500	28	0	4500	0
65	11	Qiqihar	3	35	0	1400	0	0	1400	0
66	11	Qiqihar	3	90	0	1500	56	0	1500	1500
67	11	Qiqihar	5	80	175	2000	30	75	500	1000
68	12	Daqing	3	100	50	1200	0	450	300	0
69	12	Daqing	7	200	0	3750	60	0	3750	2000
70	12	Daqing	6	85	50	2400	0	450	600	500
71	12	Daqing	4	200	20	3000	0	180	2000	0
72	12	Daqing	5	130	450	250	20	50	250	1000
73	13	Daqing	5	130	50	100	90	200	400	0
74	13	Daqing	5	120	225	600	90	25	2400	1000
75	13	Daqing	4	80	225	600	0	25	2400	2000
76	13	Daqing	4	120	0	600	75	100	900	1500
77	13	Daqing	3	120	375	125	45	125	375	1200
78	14	Jiamusi	4	80	0	2400	75	100	1600	0
79	14	Jiamusi	3	100	0	450	0	0	1050	2000
80	14	Jiamusi	2	120	0	900	0	0	2100	1000
81	14	Jiamusi	4	200	150	1000	0	0	1000	3000
82	14	Jiamusi	5	180	0	1000	0	0	1000	2000
83	14	Jiamusi	5	140	90	1000	0	10	1000	3000
84	14	Jiamusi	4	150	135	1200	0	15	1800	2000
85	15	Mudanjiang	5	140	2000	350	0	0	3150	4000
86	15	Mudanjiang	4	85	1800	0	0	450	3500	5000
87	15	Mudanjiang	4	80	1800	0	0	200	4000	4500
88	15	Mudanjiang	3	90	400	1050	8.5	100	450	3000
89	15	Mudanjiang	4	100	0	100	90	0	900	8000
90	16	Mudanjiang	4	60	2500	1250	0	2500	1250	0
91	16	Mudanjiang	4	60	500	1250	15	500	1250	0
92	16	Mudanjiang	3	50	100	1250	15	900	1250	0
93	16	Mudanjiang	4	80	600	1250	15	400	1250	1000
94	16	Mudanjiang	4	60	500	1250	15	500	1250	0
95	16	Mudanjiang	4	60	500	1250	15	500	1250	0
96	16	Mudanjiang	5	80	500	1250	15	500	1250	0
97	16	Mudanjiang	4	80	500	1250	15	500	1250	0
98	17	Heihe	5	80	0	2000	0	1500	3000	0
99	17	Heihe	5	135	0	2500	0	0	2500	1000
100	17	Heihe	4	100	50	3600	0	450	2400	0
101	17	Heihe	7	120	0	500	0	0	4500	0
102	17	Heihe	4	120	0	400	0	0	1600	2000
103	17	Heihe	3	100	0	250	0	0	2250	0
104	17	Heihe	4	100	0	100	0	0	400	1000
105	17	Heihe	4	200	0	50	0	0	450	1000
106	18	Heihe	2	50	150	1080	25	1350	720	0
107	18	Heihe	2	50	150	6300	75	350	2700	500
108	18	Heihe	5	110	65	8000	75	260	2000	2000
109	18	Heihe	3	100	225	600	25	25	2400	2000
110	18	Heihe	4	100	30	2500	15	270	0	2000
111	18	Heihe	3	135	1050	2100	25	450	900	3000
112	18	Heihe	4	45	25	3000	50	225	0	1000
113	18	Heihe	3	50	135	1800	50	15	1200	1500

Table A1 (*continued*)

HN[a]	VN[b]	Prefecture	HP[c]	HRA[d]	ACEC[e] [kg]			AHEC[f] [kg]		
					Firewood	CR[g]	LPG[h]	Firewood	CR	Coal
114	19	Jixi	5	120	1800	600	0	200	2400	4000
115	19	Jixi	4	100	525	1600	0	1225	1600	4500
116	19	Jixi	5	80	1800	700	0	450	2800	4000
117	19	Jixi	5	130	2500	350	0	0	3150	4000
118	19	Jixi	4	80	1800	0	0	200	4000	4500
119	19	Jixi	4	120	600	1500	0	400	1000	4200
120	19	Jixi	4	100	900	450	30	100	1050	4000

[a] HN: Household number.
[b] VN: Village number.
[c] HP: Household population.
[d] HRA: Household residential area.
[e] ACEC: Annual cooking energy consumption.
[f] AHEC: Annual heating energy consumption.
[g] CR: Crop residues.
[h] LPG: liquefied petroleum gas.

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